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Normalization alters the interpretation of hip strength in established unilateral lower limb prosthesis users

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ABSTRACT

Background: Valid comparisons of muscle strength between individuals or legs that differ in size requires normalization, often by simple anthropometric variables. Few studies of muscle strength in lower-limb prosthesis users have normalized strength data by any anthropometric variable, potentially confounding our understanding of strength deficits in lower-limb prosthesis users. The objective of this pilot study was to determine the need for as well as effectiveness and impact of normalizing hip strength in lower-limb prosthesis users.
Methods: Peak isometric hip extension and abduction torques were collected from 28 lower-limb prosthesis users. Allometric scaling was used to determine if hip torque values were significantly associated with, and therefore needed to be adjusted for, body mass, thigh length, or body mass x thigh length, and whether normalization was effective in reducing any associations. Between limb differences in peak hip torque, and correlations with balance ability, were inspected pre- and post-normalization.
Findings: Hip torques were consistently and significantly associated with body-mass x thigh length. Associations between peak hip torque and body-mass x thigh length were reduced by normalization. After normalization by body-mass x thigh length, between limb differences in hip extension torque, as well as the correlation between hip abduction torque and balance ability, changed from non-significant to significant.
Interpretation: In the absence of normalization, hip strength (i.e., peak torque) in lower-limb prosthesis users remains dependent on basic anthropometric variables, masking relationships between hip strength and balance ability, as well as between limb differences.

1. Introduction

Normalization of muscle function data is uncommon in lower-limb prosthesis (LLP) user research (Hewson et al., 2020), potentially causing the field to misinterpret patterns of muscle weakness, and overlook important relationships between the varied aspects of muscle function (i.e., muscle strength, power, or endurance) (Beaudart et al., 2019), and walking or balance ability. Valid comparisons of muscle function between individuals or legs that differ in size requires normalization (Bazett-Jones et al., 2011; Folland et al., 2008; Hurd et al., 2011). Normalization can be achieved by scaling measures of muscle function to one or a combination of simple anthropometric variables like body mass, height, or segment length, which serve as proxy measures for factors known to positively influence the generation of muscle force or torque (e.g., muscle mass, muscle moment arm length) (Hurd et al., 2011; Jaric, 2002; Jaric, 2003). A recent review of muscle function in LLP users (Hewson et al., 2020) however, found that less than a third of published studies normalized muscle strength data (i.e., peak torque) by any anthropometric variable. As a result, reported differences in strength, or the lack thereof, between individuals and/or legs may be confounded by differences in body size. Studies that did normalize peak torque, did so using body mass alone (Crozara et al., 2019; Heitzmann et al., 2020; Kowal and Rutkowska-Kucharska, 2014; Lloyd et al., 2010; Rutkowska-Kucharska et al., 2018; Sibley et al., 2021; Slater et al., 2021), a choice likely attributable to the popular view that larger individuals possess more muscle mass and are therefore stronger than smaller individuals (Jaric, 2002). Increases in body mass however, are not universally associated with increases in muscle mass and the

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ability to generate greater muscle force or torque (Folland et al., 2008). Further, there is no evidence to suggest that the normalization of muscle function data in LLP users by body mass, or any other anthropometric variable, is required or effective in establishing anthropometric-independent measures of muscle function that are suitable for comparison between individuals or legs that differ in size. The limited application of normalization to muscle function data in LLP user research, coupled with the lack of evidence to guide the selection of effective normalization procedures, limits the analysis and understanding of impairments in muscle function, as well as their impact on LLP users' physical function.

The objective of this pilot study was therefore to address three questions. First, is normalization of muscle strength data (i.e., peak torque) required in LLP users (i.e., is muscle strength significantly associated with common anthropometric variables)? Second, is normalization effective (i.e., does it return strength measures that are independent of anthropometric variables)? And third, does normalization alter the interpretation of strength data in LLP users? Answers to these questions were sought by analyzing peak torque data from two muscle groups central to LLP users' physical function, the hip abductors and extensors.

2. Methods

2.1. Study design

A cross-sectional pilot study was conducted to determine the need for, as well as effectiveness and impact of, normalizing maximum voluntary isometric hip peak torque by conventional anthropometric variables in established unilateral LLP users. Study protocols were reviewed and approved by an institutional review board at the University of Illinois at Chicago. All individuals gave written informed consent before participating.

2.2. Participant recruitment

Individuals with a unilateral transtibial or transfemoral amputation due to trauma, dysvascular complications, cancer, or infection were recruited from prosthetic clinics in Chicago using convenience sampling. To participate, individuals were required to be 18 years of age or older; have a history of wearing a prosthesis for at least two years post amputation; be able to walk 10 m without the use of a cane or walker; and be able to read, write, and speak English. Participants were excluded if they had a second amputation, contralateral complications, or a neuromusculoskeletal or cardiopulmonary condition (e.g., Chronic Obstructive Pulmonary Disease) that would preclude them from completing testing procedures.

2.3. Data collection

2.3.1. Participant characterization

Participant age and sex were collected via self-report, while amputation characteristics (e.g., etiology) Medicare Functional Classification Level (MFCL), or K-level (Palmento Government Benefits Administrators, 1994), and hours of prosthesis use per day were determined via interview by a certified prosthetist. Perceived mobility was assessed with the Prosthetic Limb Users Survey – Mobility (PLUS-M) (Hafner et al., 2017), while balance ability and number of co-morbidities were characterized by distance walked on the Narrowing Beam Walking Test (NBWT) (Sawers and Hafner, 2018a), and the Charlson Comorbidity Index (CCI) (Chaudhry et al., 2005), respectively. The NBWT was chosen for its challenge to lateral balance control (Sawers and Hafner, 2018a; Sawers and Ting, 2015), the ensuing demand placed on hip abductor muscle function (Curtze et al., 2010; Sawers et al., 2015), and its psychometric properties among unilateral LLP users (Sawers et al., 2020; Sawers and Hafner, 2018b).

Three anthropometric variables recognized for their potential influence on muscle strength were tested for their association with peak isometric hip extension and abduction torque: body mass (BM), thigh length (TL), and the product of body mass and thigh length (BM x TL) (Jaric, 2002; Jaric et al., 2005). Transfemoral amputation disrupts the relationship between height and muscle moment arm length in the residual limb because the length of the residual limb (i.e., thigh) is no longer proportional to body height. Thigh length (or residual limb length) was therefore selected in lieu of height as a proxy for muscle moment arm length. Residual limb thigh length in transfemoral prosthesis users was measured as the distance from the ischium to the distal end of the residuum.

2.3.2. Hip torque data collection

Maximum voluntary isometric hip extension and abduction torques were measured using a motor-driven dynamometer (Biodex System 4 Pro, Biodex Medical Systems, Inc., Shirley, NY) (Drouin et al., 2004). When testing hip extension or abduction, participants were positioned in a supine position (Meyer et al., 2013; Rutkowska-Kucharska et al., 2018) with the hip flexed to 20 degrees (Powers et al., 1996), or a side-lying position (Lloyd et al., 2010; Meyer et al., 2013; Nadollek et al., 2002; Widler et al., 2009), with the hip abducted to 10 degrees (Meyer et al., 2013; Powers et al., 1996), respectively. A supine rather than prone position was chosen for the assessment of hip extension for participant comfort, and for consistency with previous research (Hewson et al., 2020). The order of testing (i.e., leg and muscle group) was randomized, and the prosthesis was removed when testing the residual limb (Rutkowska-Kucharska et al., 2018; Ryser et al., 1988). After three-submaximal practice trials (Broekmans et al., 2013), participants completed 15 five-second maximum voluntary effort trials with 10 s rest between each trial. Participants were instructed to generate their maximum isometric force as quickly as they could, and to hold that maximum force until told to relax. The analog signal from the dynamometer was sampled at 1000 Hz, starting just before the verbal "go" command was given. Verbal encouragement was provided throughout the 5-s contraction. Five-minute rest periods were enforced between testing positions.

2.4. Data processing and analysis

2.4.1. Hip torque data processing

The maximum voluntary isometric torque for each muscle group and leg was derived from the digitized analog signal (NI USB-6341, National Instruments, Austin, TX), adjusted for the effects of gravity, and smoothed using a low-pass Svetsky-Golay filter. Peak torque was computed as the maximum torque recorded between signal onset and offset across all 15 trials. All processing and analysis steps were performed using custom MATLAB (MathWorks, Natick, MA) routines.

2.4.2. Normalization procedure

Allometric scaling (Jaric, 2002; Nevill et al., 2005; Owings et al., 2002; Vanderburgh et al., 1995) was used to determine *if* maximum voluntary isometric hip torque needed to be adjusted for the influence of anthropometric variables, and whether any needed adjustments were *effective* in returning a measure of hip torque that was independent of anthropometric variables in unilateral LLP users. Non-normalized hip torque (i.e., muscle strength) (S) was modeled as a function of a confounding anthropometric scaling variable (X), by the power function:

$$S = S_n(X)^{\beta} \quad (1)$$

where (S_n) is normalized hip strength (i.e., peak torque), and (β) is the scaling exponent (Jaric, 2002; Kleiber, 1950; Nevill et al., 1992; Nevill et al., 2005). *Re*-writing Eq. (1), normalized hip strength (S_n) can be represented as:

$$S_n = S \Big/ (X)^{\beta} \tag{2}$$

To determine the appropriate value for the scaling exponent (β) the power function (Eq. (1)) is linearized with a log-transformation, yielding:

$$log\ (S) = log\ (S_n) + \beta\ (log\ X) \tag{3}$$

As the equation of a straight line, the scaling exponent (β) represents the slope of that line. The value of the slope can be estimated by performing a standard linear regression with log (S) as the dependent variable, and log (X) as the independent variable. To determine whether the slope of the log-transformed regression is significantly greater than zero, and hip strength is significantly associated with the anthropometric variable in question, the 95% confidence interval (CI) of the slope is inspected to determine whether it includes the values zero or 1. Table 1 describes how to interpret the 95% CI of the slope for significance and if normalization is needed (i.e., if an association exists), as well as how normalization should be applied (Owings et al., 2002).

2.4.3. Statistical analysis

Departures from normality among continuous variables were evaluated with Shapiro-Wilk tests (Shapiro and Wilk, 1965). Outliers were detected and removed if they exceeded a threshold of ±3.0 median absolute deviations (MAD) beyond the median (Leys et al., 2013). Measures of central tendency and dispersion, as well as frequency and proportion, were computed to describe the continuous and categorical characteristics of the study sample, respectively. As an initial assessment of whether normalization alters the interpretation of hip strength in unilateral LLP users, Spearman's rho coefficients were computed between peak hip abduction torque and NBWT performance prior to and following normalization. Wilcoxon signed rank tests were also run to test for differences in peak hip extension torque between the residual and intact limbs before and after normalization. The level of significance for all tests was set to $\alpha \leq 0.05$. Normalization procedures and statistical analyses were performed using SPSS v.28 (Chicago, IL).

3. Results

Twenty-eight unilateral lower limb prosthesis (LLP) users participated in the study. Age, body mass index (BMI), and NBWT scores were normally distributed ($W \geq 0.952$, $p \geq .256$). The remaining amputation, health, and mobility-related continuous variables were non-normally distributed ($W \leq 0.899$, $p \leq .015$). Body mass (BM) (mean ± 95% CI) (83.8 kg ±16.4), height (1.73 m ±0.07), and intact thigh length (TL) (0.42 m ±0.02) were normally distributed ($W \geq 0.949$, $p \geq .216$), while residual limb thigh length (median ± MAD) (0.36 m ±0.13) was non-normally distributed ($W = 0.905$, $p = .021$).

Prior to log-transformation, and regardless of leg, non-normalized peak isometric hip extension and abduction torque values were non-normally distributed ($W \leq 0.770$, $p \leq .001$). Following their log-transformation non-normalized torque values were normally distributed ($W \geq 0.913$, $p \geq .112$). Torque values from two participants, one transtibial and one transfemoral, were found to exceed the outlier threshold of median ± 2.5 median absolute deviations (Leys et al., 2013) and were therefore excluded from subsequent analyses. Hence, 26 participants remained in the final analysis (Tables 2 and 3).

Within the residual limb, the slope coefficients (i.e., scaling exponent (β)) of linearized regression equations between non-normalized peak isometric hip torques and body mass (BM), as well as thigh length (TL), were not significantly greater than zero (Table 4). In contrast, slopes of the linearized regression equations between residual limb hip torques and BM x TL were significantly greater than zero (Table 4). Within the intact limb, slope coefficients of linearized regression equations between non-normalized peak isometric hip torques and all anthropometric variables (i.e., BM, TL, and BM x TL) were significantly greater than zero (Table 4).

After normalizing residual and intact limb peak hip extension and abduction torques by BM x TL, the slopes of the respective linearized regression equations were no longer significantly greater than zero (i.e., confidence intervals included 0 but not 1, no significant association) (Table 5). Similarly, after normalizing intact limb peak torques by body mass, the slopes of the linearized regression equations were no longer significantly greater than zero. In contrast, when intact hip extension and abduction torques were normalized by thigh length, the slopes of the linearized regression equations were indeterminant (i.e., confidence intervals included 0 and 1) (Table 5).

Prior to normalization the correlation between intact limb hip abduction torque and balance performance (i.e., NBWT distance walked) was small and not statistically significant ($r_s = 0.316$, $p = .109$). Once normalized by BM x TL intact limb hip abduction torque was moderately and significantly correlated with NBWT performance ($r_s = 0.513$, $p = .006$). Differences in hip extension torque between the intact and residual limb were also affected by normalization. Initially, no significant difference was found between intact and residual limb hip extension torques (intact: 71.4 Nm, residual: 72.9 Nm; $Z = -0.102$, $p = .918$). However, once normalized by BM x TL the same between limb difference was statistically significant (intact: 8.39 (% BM X TL), residual: 24.5 (% BM X TL); $Z = -4.60$, $p < .001$).

4. Discussion

The objective of this pilot study was to determine the need for as well as effectiveness and impact of normalizing hip extension and abduction muscle strength, as estimated by peak isometric torque, in LLP users. Results suggest that hip extension and abduction strength are significantly and consistently associated with body mass x thigh length in unilateral LLP users, which when adjusted for, alters the interpretation of between limb differences in hip extension strength, as well as the relationship between hip abduction strength and balance ability. Except for amputation etiology and sex, participant characteristics (e.g., age, amputation level, PLUS-M T-scores,) were largely consistent with those reported in large national studies of LLP users (i.e., $n = 146$–1568) (Ehde et al., 2000; Hafner et al., 2016; Pezzin et al., 2000; Wurdeman et al., 2018; Ziegler-Graham et al., 2008). The results of this pilot study may therefore generalize to the broader population of established unilateral non-dysvascular LLP users.

Table 1
Interpretation of the 95% confidence intervals (CI) accompanying the slope (β) of log-log regressions.

95% CI	Slope of log-log regression	Association between strength and anthropometric variable	Normalization
includes zero, not 1	slope *not* significantly > zero	*no* significant association	not indicated
includes 1, not zero	slope significantly > zero	significant *linear* association	indicated; $Sn = S/(X)^1$
between zero and 1	slope significantly > zero	significant *non-linear* association	indicated; $Sn = S/(X)^{\beta}$
includes zero and 1	slope indeterminant	association is indeterminant	N/A

Table 2
Participant demographic, health, amputation, mobility, and balance-related characteristics.

Demographics		Health		Amputation			Balance and Mobility			
Age	Sex	CCI	BMI	Level	Etiology	Time Since Amputation (*years*)	MFCL	PLUS-M (*T-score*)	Prosthetic Use (*hrs/day*)	NBWT (*/1.0*)
Mean (95% CI)	Subjects (/26)	Median (MAD)	Mean (95% CI)	Subjects (/26)	Subjects (/26)	Median (MAD)	Subjects (/26)	Mean (95% CI)	Median (MAD)	Mean (95% CI)
53.7 (47.7, 59.7)	Male (n = 13) Female (*n* = 13)	1.0 (1.5)	27.9 (25.3, 30.5)	Transtibial (n = 13) Transfemoral (n = 13)	Non-dysvascular (*n* = 19) Dysvascular (*n* = 7)	12.0 (13.3)	K2 (*n* = 12) K3 (n = 14)	51.1 (48.0, 54.2)	14.0 (2.97)	0.44 (0.35, 0.53)

BMI: Body Mass Index; CCI: Charlson Co-morbidity Index; CI: Confidence Interval; MAD: Median Absolute Deviation; MFCL: Medicare Functional Classification Level (K-level); NBWT: Narrowing Beam Walking Test; PLUS-M: Prosthetic Limb Users Survey-Mobility.

Table 3
Non-normalized residual and intact limb peak isometric hip extension and abduction torques.

	Hip extensors		Hip abductors	
	Residual limb	Intact limb	Residual limb	Intact limb
	Median (MAD)	Median (MAD)	Median (MAD)	Median (MAD)
Non-normalized peak torque (Nm)	72.9 (17.8)	71.4 (12.2)	81.4 (12.0)	74.3 (17.6)

MAD: Median Absolute Deviation.

Table 4
The slopes (β-values) and accompanying 95% confidence intervals (CI) of linear regressions performed on the logarithm of *non-normalized* hip extensor and abductor maximum voluntary isometric peak torque and the logarithm of body mass (BM), thigh length (TL), or body mass x thigh length (BM x TL).

	Hip extensors		Hip abductors	
	Residual limb	Intact limb	Residual limb	Intact limb
	β (95% CI [LB, UB])	β (95% CI [LB, UB])	β (95% CI [LB, UB])	β (95% CI [LB, UB])
Body mass (BM)	0.44 (−0.08, 0.95)[a]	0.60 (0.22, 1.1)[b]	0.44 (−0.10, 0.98)[a]	0.80 (0.29, 1.3)[b]
Thigh length (TL)	0.31 (−0.16, 0.77)[a]	2.9 (0.73 5.0)[b]	0.38 (−0.10, 0.85)[a]	2.9 (0.38, 5.3)[b]
BM x TL	0.33 (0.01, 0.64)[c]	0.61 (0.24, 0.97)[c]	0.35 (0.036, 0.67)[c]	0.73 (0.29, 1.2)[b]

β: slope coefficient; BM: body mass; CI: confidence interval; LB: lower bound; TL: thigh length; UB: upper bound.
a: no significant association between peak torque and anthropometric variable (CI includes 0 and not 1, $p \geq .05$).
b: significant linear association between peak torque and anthropometric variable (CI includes 1 or greater but not 0, $p < .05$).
c: significant non-linear association between peak torque and anthropometric variable (CI between 0 and 1, $p < .05$).

Table 5
The slopes (β-values) and accompanying 95% confidence intervals (CI) of linear regressions performed on the logarithm of *normalized* hip extensor and abductor maximum voluntary isometric peak torque and the logarithm of body mass (BM), thigh length (TL), or body mass x thigh length (BM x TL).

	Hip extensors		Hip abductions	
	Residual limb	Intact limb	Residual limb	Intact limb
	β (90% CI [LB, UB])	β (90% CI [LB, UB])	β (90% CI [LB, UB])	β (90% CI [LB, UB])
Body mass (BM)	–	−0.36 (−0.78, 0.10)[a]	–	−0.20 (−0.71, 0.32)[a]
Thigh length (TL)	–	1.9 (−0.27, 4.0)[c]	–	1.9 (−0.63, 4.3)[c]
BM x TL	0.00 (−0.32, 0.32)[a]	0.00 (−0.37, 0.37)[a]	0.00 (−0.32, 0.32)[a]	−0.27 (−0.71, 0.17)[a]

β: slope coefficient; BM: body mass; CI: confidence interval; TL: thigh length LB: lower bound; TL: thigh length; UB: upper bound.
a: no significant association between peak torque and anthropometric variable (CI includes 0 and not 1, $p \geq .05$).
b: significant linear association between peak torque and anthropometric variable (CI includes 1 or greater but not 0, $p < .05$).
c: association between peak torque and anthropometric variable is indeterminant (CI includes both 0 and 1).

4.1. Is hip strength, as estimated by peak isometric torque, significantly associated with anthropometric variables in unilateral LLP users and therefore in need of normalization?

Non-normalized peak isometric hip extension and abduction torques in the residual limb of unilateral LLP users were found to be significantly associated with body mass x thigh length (BM x TL), but not body mass (BM) or thigh length (TL) alone. In contrast, non-normalized peak isometric hip extension and abduction torques in the intact limb were significantly associated with all three anthropometric variables. Across residual and intact limbs, BM x TL was the only anthropometric variable that both hip extension and abduction strength were consistently dependent on, and for which adjustment was needed. The lack of a significant association between non-normalized hip torques and BM or TL in the residual limb may be due to amputation-related changes. Increases in BM may not be accompanied by expected increases in fat-free muscle mass within the residual limb. While strength has been correlated with muscle physiological cross-sectional area (Maughan et al., 1983), increased BM does not necessarily lead to increased fat-free muscle mass and force generating capacity (Folland et al., 2008). Similarly, amputation may alter muscle moment arm length in the residual limb. To date, BM has been the only anthropometric variable with which dynamometer-driven measures of hip torque in LLP users have been normalized (Crozara et al., 2019; Heitzmann et al., 2020; Kowal and Rutkowska-Kucharska, 2014; Lloyd et al., 2010; Rutkowska-Kucharska et al., 2018; Sibley et al., 2021; Slater et al., 2021). Our understanding of hip muscle strength in unilateral LLP users, and its relationship to physical function, is therefore currently limited to measures of hip torque that remain dependent on anthropometric variables.

4.2. Is normalization effective, and does it alter the interpretation of hip extension and abduction strength in unilateral LLP users?

Normalization of residual and intact limb peak isometric hip extension and abduction torques by BM x TL was found to reduce significant associations and return measures of hip strength that were independent of the tested anthropometric variables. Among LLP users, adjusting for the influence of BM x TL on hip extension and abduction torques yields strength indices that are suitable for comparison between individuals and legs that differ in size. Importantly, normalization by BM x TL was found to alter the interpretation of hip strength in this pilot study. Specifically, normalization of intact limb hip abduction torque by BM x TL led to the identification of a larger and significant correlation between hip abduction peak torque (i.e., muscle strength) and balance ability, as estimated by NBWT performance, that would otherwise have been overlooked in the absence of normalization. While several other factors may contribute to balance ability (e.g., socket fit, proprioception), these results suggest that a potentially important relationship between a modifiable factor, intact limb hip abduction strength, and fall risk as estimated by the NBWT (Sawers et al., 2020; Sawers and Hafner, 2018b), would go unnoticed and untreated. Additionally, previous research, which either did not normalize hip torques or did so using body mass alone, has suggested that hip extension strength in unilateral LLP users is either lower in the residual versus intact limb (James, 1973; Rutkowska-Kucharska et al., 2018), or not significantly different (Bäcklund et al., 1968; Powers et al., 1996). In contrast, the current results suggest that hip extension strength, once normalized to BM x TL, is significantly greater in the residual than the intact limb of unilateral LLP users. While limited to two specific examples, these data serve to initially illustrate how a failure to normalize hip strength data in LLP users to appropriate anthropometric variables may confound results, alter their interpretation, and ultimately influence the treatments and research questions clinicians and scientists pursue.

4.3. Future research and limitations

Future research with a larger sample is needed to confirm the current results, conduct important sub-analyses (e.g., level of amputation, etiology) (Bazett-Jones et al., 2011; Powers et al., 1996), and compare theoretical and empirical scaling exponents for LLP users (Wren and Engsberg, 2007). A comprehensive evaluation of additional aspects of muscle function (e.g., power and endurance), muscle groups (e.g., knee extensors), and muscle actions (e.g., eccentric) is required to determine whether the current results apply to the broader construct of muscle function in LLP users. Consideration for alternative normalization models that do not presume geometric similarity (e.g., a gamma function model) (Nevill et al., 2004; Nevill and Holder, 1999) and additional anthropometric scaling variables (e.g., fat free muscle mass, muscle thickness, hip girth) (Jaric, 2002) are necessary to identify and adopt the most physiologically-relevant and effective normalization procedure(s). While motor-driven dynamometers are regularly used to evaluate muscle strength in LLP users (Hewson et al., 2020), and have been shown to possess degrees of validity and reliability in other clinical populations (Drouin et al., 2004; Jørgensen et al., 2017; Kristensen et al., 2017; Lienhard et al., 2013), their psychometric properties in LLP users remain to be confirmed. Establishing key psychometric indices for motor-driven dynamometers, as well as other means of evaluating muscle function in LLP users is necessary to develop a gold-standard against which clinically-feasible assessments can be compared, and changes over time evaluated.

5. Conclusion

In this pilot study we demonstrate that hip extension and abduction strength in unilateral LLP users, as estimated by maximum voluntary isometric peak torque, are significantly and consistently associated with BM x TL. The dependence on BM x TL can be minimized via normalization to create measures of hip strength amenable to comparisons between individuals and legs that differ in size. In the absence of such procedures, important relationships between hip strength and balance ability, as well as critical between limb differences may go unnoticed. This pilot study suggests that until further research is conducted to confirm and expand upon the present findings, researchers should consider the potential confounding effects of anthropometric variables on strength data among unilateral LLP users and adjust for any significant associations accordingly. The findings of this pilot study suggest that non-normalized peak torque strength data in LLP users should be interpreted cautiously, and that the application of validated normalization procedures may challenge long-held beliefs regarding patterns of muscle weakness and their association with walking or balance ability in LLP users.

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Declaration of conflicting interest

The authors declare that there is no conflict of interest.

Institutional review

All study procedures were reviewed and approved by a University of Illinois at Chicago institutional review board.

Clinical trial registration

N/A.

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References

Bäcklund, L., Lemperg, R., Ottosson, L.G., 1968. Leg muscle strength in below-knee amputees. Acta Orthop. Scand. 39 (1), 107–116.
Bazett-Jones, D.M., Cobb, S.C., Joshi, M.N., Cashin, S.E., Earl, J.E., 2011. Normalizing hip muscle strength: establishing body-size-independent measurements. Arch. Phys. Med. Rehabil. 92 (1), 76–82.
Beaudart, C., Rolland, Y., Cruz-Jentoft, A.J., et al., 2019. Assessment of muscle function and physical performance in daily clinical practice: a position paper endorsed by the European Society for Clinical and Economic Aspects of osteoporosis, osteoarthritis and musculoskeletal diseases (ESCEO). Calcif. Tissue Int. 105 (1), 1–14.

Broekmans, T., Gijbels, D., Eijnde, B.O., et al., 2013. The relationship between upper leg muscle strength and walking capacity in persons with multiple sclerosis. Mult. Scler. 19 (1), 112–119.
Chaudhry, S., Jin, L., Meltzer, D., 2005. Use of a self-report-generated Charlson comorbidity index for predicting mortality. Med. Care 43 (6), 607–615.
Crozara, L.F., Marques, N.R., LaRoche, D.P., et al., 2019. Hip extension power and abduction power asymmetry as independent predictors of walking speed in individuals with unilateral lower-limb amputation. Gait Posture 70, 383–388.
Curtze, C., Postema, K., Akkermans, H.W., Otten, B., Hof, A.L., 2010. The narrow ridge balance test: a measure for one-leg lateral balance control. Gait Posture 32 (4), 627–631.
Drouin, J.M., Valovich-McLeod, T.C., Shultz, S.J., Gansneder, B.M., Perrin, D.H., 2004. Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. Eur. J. Appl. Physiol. 91 (1), 22–29.
Ehde, D.M., Czerniecki, J.M., Smith, D.G., et al., 2000. Chronic phantom sensations, phantom pain, residual limb pain, and other regional pain after lower limb amputation. Arch. Phys. Med. Rehabil. 81 (8), 1039–1044.
Folland, J.P., Mc Cauley, T.M., Williams, A.G., 2008. Allometric scaling of strength measurements to body size. Eur. J. Appl. Physiol. 102 (6), 739–745.
Hafner, B.J., Morgan, S.J., Askew, R.L., Salem, R., 2016. Psychometric evaluation of self-report outcome measures for prosthetic applications. J. Rehabil. Res. Dev. 53 (6), 797–812.
Hafner, B.J., Gaunaurd, I.A., Morgan, S.J., Amtmann, D., Salem, R., Gailey, R.S., 2017. Construct validity of the prosthetic limb users survey of mobility (PLUS-M) in adults with lower limb amputation. Arch. Phys. Med. Rehabil. 98 (2), 277–285.
Heitzmann, D.W.W., Leboucher, J., Block, J., et al., 2020. The influence of hip muscle strength on gait in individuals with a unilateral transfemoral amputation. PLoS One 15 (9), e0238093.
Hewson, A., Dent, S., Sawers, A., 2020. Strength deficits in lower limb prosthesis users: a scoping review. Prosthetics Orthot. Int. 44 (5), 323–340.
Hurd, W.J., Morrey, B.F., Kaufman, K.R., 2011. The effects of anthropometric scaling parameters on normalized muscle strength in uninjured baseball pitchers. J. Sport Rehabil. 20 (3), 311–320.
James, U., 1973. Maximal isometric muscle strength in healthy active male unilateral above-knee amputees, with special regard to the hip joint. Scand. J. Rehabil. Med. 5 (2), 55–66.
Jaric, S., 2002. Muscle strength testing: use of normalisation for body size. Sports Med. 32 (10), 615–631.
Jaric, S., 2003. Role of body size in the relation between muscle strength and movement performance. Exerc. Sport Sci. Rev. 31 (1), 8–12.
Jaric, S., Mirkov, D., Markovic, G., 2005. Normalizing physical performance tests for body size: a proposal for standardization. J. Strength Cond Res. 19 (2), 467–474.
Jørgensen, M., Dalgas, U., Wens, I., Hvid, L.G., 2017. Muscle strength and power in persons with multiple sclerosis - a systematic review and meta-analysis. J. Neurol. Sci. 376, 225–241.
Kleiber, M., 1950. Physiological meaning of regression equations. J. Appl. Physiol. (1985) 2 (7), 417–423.
Kowal, M., Rutkowska-Kucharska, A., 2014. Muscle torque of the hip joint flexors and extensors in physically active and inactive amputees. Biomed. Hum. 6 (1), 63–68.
Kristensen, O.H., Stenager, E., Dalgas, U., 2017. Muscle strength and poststroke hemiplegia: a systematic review of muscle strength assessment and muscle strength impairment. Arch. Phys. Med. Rehabil. 98 (2), 368–380.
Leys, C., Ley, C., Klein, O., Bernard, P., Licata, L., 2013. Detecting outliers: do not use standard deviation around the mean, use absolute deviation around the median. J. Exp. Soc. Psychol. 49 (4), 764–766.
Lienhard, K., Lauermann, S.P., Schneider, D., Item-Glatthorn, J.F., Casartelli, N.C., Maffiuletti, N.A., 2013. Validity and reliability of isometric, isokinetic and isoinertial modalities for the assessment of quadriceps muscle strength in patients with total knee arthroplasty. J. Electromyogr. Kinesiol. 23 (6), 1283–1288.
Lloyd, C.H., Stanhope, S.J., Davis, I.S., Royer, T.D., 2010. Strength asymmetry and osteoarthritis risk factors in unilateral trans-tibial, amputee gait. Gait Posture 32 (3), 296–300.
Maughan, R.J., Watson, J.S., Weir, J., 1983. Strength and cross-sectional area of human skeletal muscle. J. Physiol. 338, 37–49.
Meyer, C., Corten, K., Wesseling, M., et al., 2013. Test-retest reliability of innovated strength tests for hip muscles. PLoS One 8 (11), e81149.
Nadollek, H., Brauer, S., Isles, R., 2002. Outcomes after trans-tibial amputation: the relationship between quiet stance ability, strength of hip abductor muscles and gait. Physiother. Res. Int. 7 (4), 203–214.
Nevill, A.M., Holder, R.L., 1999. Identifying population differences in lung function: results from the Allied Dunbar national fitness survey. Ann. Hum. Biol. 26 (3), 267–285.
Nevill, A.M., Ramsbottom, R., Williams, C., 1992. Scaling physiological measurements for individuals of different body size. Eur. J. Appl. Physiol. Occup. Physiol. 65 (2), 110–117.
Nevill, A.M., Stewart, A.D., Olds, T., Holder, R., 2004. Are adult physiques geometrically similar? The dangers of allometric scaling using body mass power laws. Am. J. Phys. Anthropol. 124 (2), 177–182.
Nevill, A.M., Bate, S., Holder, R.L., 2005. Modeling physiological and anthropometric variables known to vary with body size and other confounding variables. Am. J. Phys. Anthropol. 141–153. Suppl 41.
Owings, T.M., Pavol, M.J., Grabiner, M.D., 2002. Lower extremity muscle strength does not independently predict proximal femur bone mineral density in healthy older adults. Bone 30 (3), 515–520.
Palmento Government Benefits Administrators, 1994. Lower limb prostheses. In: DMERC Medicare Advis December, pp. 99–105.
Pezzin, L.E., Dillingham, T.R., MacKenzie, E.J., 2000. Rehabilitation and the long-term outcomes of persons with trauma-related amputations. Arch. Phys. Med. Rehabil. 81 (3), 292–300.
Powers, C.M., Boyd, L.A., Fontaine, C.A., Perry, J., 1996. The influence of lower-extremity muscle force on gait characteristics in individuals with below-knee amputations secondary to vascular disease. Phys. Ther. 76 (4), 369–377.
Rutkowska-Kucharska, A., Kowal, M., Winiarski, S., 2018. Relationship between asymmetry of gait and muscle torque in patients after unilateral transfemoral amputation. Appl Bionics Biomech. 1–9.
Ryser, D.K., Erickson, R.P., Cahalan, T., 1988. Isometric and isokinetic hip abductor strength in persons with above-knee amputations. Arch. Phys. Med. Rehabil. 69 (10), 840–845.
Sawers, A., Hafner, B.J., 2018a. Narrowing beam-walking is a clinically feasible approach for assessing balance ability in lower-limb prosthesis users. J. Rehabil. Med. 50 (5), 457–464.
Sawers, A., Hafner, B., 2018b. Validation of the narrowing beam walking test in lower limb prosthesis users. Arch. Phys. Med. Rehabil. 99 (8), 1491–1498.
Sawers, A., Ting, L.H., 2015. Beam walking can detect differences in walking balance proficiency across a range of sensorimotor abilities. Gait Posture 41 (2), 619–623.
Sawers, A., Allen, J.L., Ting, L.H., 2015. Long-term training modifies the modular structure and organization of walking balance control. J. Neurophysiol. 114 (6), 3359–3373.
Sawers, A., Kim, J., Balkman, G., Hafner, B.J., 2020. Interrater and test-retest reliability of performance-based clinical tests administered to established users of lower limb prostheses. Phys. Ther. 100 (7), 1206–1216.
Shapiro, S.S., Wilk, M.B., 1965. An analysis of variance test for normality. Biometrika 52 (3/4), 591–611.
Sibley, A.R., Strike, S., Moudy, S.C., Tillin, N.A., 2021. The associations between asymmetries in quadriceps strength and gait in individuals with unilateral transtibial amputation. Gait Posture 90, 267–273.
Slater, L., Finucane, S., Hargrove, L.J., 2021. Knee extensor power predicts six-minute walk test performance in people with transfemoral amputations. PM R 14 (4), 445–451.
Vanderburgh, P.M., Mahar, M.T., Chou, C.H., 1995. Allometric scaling of grip strength by body mass in college-age men and women. Res. Q. Exerc. Sport 66 (1), 80–84.
Widler, K.S., Glatthorn, J.F., Bizzini, M., et al., 2009. Assessment of hip abductor muscle strength. A validity and reliability study. J. Bone Joint Surg. Am. 91 (11), 2666–2672.
Wren, T.A.P., Engsberg, J.R.P., 2007. Normalizing lower-extremity strength data for children without disability using allometric scaling. Arch. Phys. Med. Rehabil. 88 (11), 1446–1451.
Wurdeman, S.R., Stevens, P.M., Campbell, J.H., 2018. Mobility analysis of AmpuTees II: comorbidities and mobility in lower limb prosthesis users. Am. J. Phys. Med. Rehab. 97 (11), 782–788.
Ziegler-Graham, K., MacKenzie, E.J., Ephraim, P.L., Travison, T.G., Brookmeyer, R., 2008. Estimating the prevalence of limb loss in the United States: 2005 to 2050. Arch. Phys. Med. Rehabil. 89 (3), 422–429.